Extratropical Forcing of Submonthly Variations of Rainfall in Vietnam

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ABSTRACT

An EOF analysis is applied to high-resolution Vietnam Gridded Precipitation anomalies to support the notion that the characteristics of intraseasonal oscillation (ISO) of rainfall in Vietnam are distinct from location to location and highly affected by topography. Power spectral analysis reveals that the ISO of rainfall in Vietnam is dominated by submonthly-scale ISO (SISO), which is most active in September–October. The rainfall SISO shows remarkable relationships with heavy rainfall days in the Red River Delta and Mid-Central and Central Highlands but relatively weak correlations with heavy rainfall days in the Northeast and Southern Plain. A composite technique applied to filtered OLR and ERA-Interim shows that the first four principal components (PCs) of the rainfall SISO involve four different processes that closely relate to extratropical systems. The rainfall SISO in the PC1 is governed by interaction between the pressure surge induced by the submonthly amplifications of the Siberian high and tropical depressions (TDs). Rainfall SISO in PC2 is modulated by the convergence of the southward excursion of the polar air mass and TD-type waves. Rainfall SISO in PC3 is generated by the quasigeostrophic lifting of the extratropical wave train associated with TD-type waves. The effect of upstream development of the wave train from the North Pacific and TD-type wave is the key process inducing the rainfall SISO in PC4.

1. Introduction

Vietnam is situated in a transition region of the Indian summer monsoon, northwestern Pacific (NWP) summer monsoon, and East Asian summer monsoon (Wang and LinHo 2002). Thus, its climate is characterized by strong interactions among these monsoon systems. Furthermore, the territory of Vietnam extends north–south broadly; its terrain is complex and characterized by high mountains, highlands, and two flat deltas in the northern and southern parts of the country (Fig. 1). This terrain complexity influences the tropical and extratropical monsoon components that lead to a great diversity of Vietnam’s climate (Nguyen et al. 2014; Phan-Van et al. 2018).

As with other climate variables, rainfall in Vietnam displays distinct characteristics and involves a variety of synoptic patterns. Based on the Köppen climate classification method (Köppen 1936), Vietnam has been divided into seven subregions: the Northwest, Northeast, Red River Delta, North Central, South Central, Central Highlands, and Southern Plain (Fig. 1) (Nguyen and Nguyen 2004; Nguyen et al. 2014). The rainy season in the first three subregions (i.e., northern Vietnam) generally starts in April–May and ends in October with a rainfall peak in July–August. The main factors that modulate rainfall in these subregions are cold surges, early summer tropical cyclones, a northward-migrating intertropical convergence zone (ITCZ), and mesoscale convective systems. The rainy season in southern Vietnam, including the Central Highlands and Southern Plain, is bimodal and characterized by the typical seasonal cycle of the South Asian monsoon. The two rainfall peaks occur in June and October, and this pattern is consistent with the seasonal migration of the ITCZ combined with the evolutions of the NWP subtropical high, the Australian high, and low-level cross-equatorial flows (Nguyen et al. 2014). However, because of the foehn wind across the Truong Son Mountains, the summer months are not coincident with rainy season in the coastal North Central and South Central regions (Nguyen-Le et al. 2014). Rainfall in these subregions is basically caused by late fall–early winter tropical cyclones and the combined effect of cold surges, tropical easterly disturbances, and topography (Chen et al. 2012a; Nguyen-Le and Matsumoto 2016; van der Linden et al. 2016a; Yokoi and Matsumoto 2008).

Intraseasonal oscillation (ISO) plays an essential role in modulating rainfall in the Asian summer monsoon region. On the eastern coast of the Indochina Peninsula...
where Vietnam is located, rainfall also exhibits two dominant modes of oscillations of 10–20 and 30–60 days (Yokoi and Satomura 2005, 2006; Yokoi et al. 2007). According to these studies, the 10–20-day mode is most active in northern Vietnam in May and September whereas it reaches its peak in central Vietnam in August–November. This north–south contrast of the submonthly rainfall behavior is attributed to the seasonal southward migration of the northwestward-propagating vorticity disturbances across the IP. In a different manner, the 30–60-day mode shows the largest variance in the Central subregion only and is the most active from July to October. The large-scale circulation associated with this mode is viewed as a northeastward movement of 30–60-day oscillation over the NWP to the IP.

In addition to the above modes, the Madden–Julian oscillation (MJO), equatorial Rossby (ER) waves, Kelvin waves, and their interactions also influence daily rainfall variations in southern Vietnam (van der Linden et al. 2016b). While the MJO possesses the largest effects in both magnitude and spatial extent, ER waves have a smaller impact and show noticeable amplitudes in the northern areas of southern Vietnam. The effect of Kelvin waves is the third greatest and it mainly prevails over the regions south of 12°N. It was also shown that mixed Rossby–gravity and eastward inertio-gravity waves are frequently observed over the central Pacific and have weak impacts on rainfall variations in southern Vietnam (Kiladis et al. 2016; Takayabu and Nitta 1993; van der Linden et al. 2016b).

Heavy rainfall occurs very often during the rainy season and causes severe floods and landslides in Vietnam. A number of case studies, therefore, have been conducted to uncover the mechanisms of heavy rainfall in the country. In central Vietnam, the combined effect of TD-type waves (6–10 days), early-winter cold surges (10–24 days), and topography is considered the decisively important mechanism for heavy rainfall to develop (Chen et al. 2012b; van der Linden et al. 2016a; Wu et al. 2012; Yokoi and Matsumoto 2008). The cold surge leads to a surge of northwesterlies to the sea between Vietnam and the Philippines (known as Bien Dong in Vietnam), which enhances and then blows the preexisting convection against the Truong Son Mountains, resulting in extreme orographic rainfall. In northern Vietnam, it is argued that the interplay between TD-type disturbances and northerly monsoonal flows creates a strong low-level convergence and, therefore, plays an essential role in inducing heavy rainfall in this subregion (Wu et al. 2011). In another study, Chen et al. (2012c) pointed out that the interactions between three distinct monsoon modes, namely, easterly disturbances, cold surges, and the MJO, provide a favorable environment for the establishment of heavy rainfall in northern Vietnam. In a different manner, heavy rainfall in the southern Vietnam subregion is increased in the wet phases of the MJO and convectively coupled equatorial waves. While the MJO affects the depth of moist westerly monsoon flow and vertical wind shear, ER waves somewhat constrain the lower-tropospheric humidity that supports the growth of deep convection in their wet phases. However, the changes of wind and humidity profile favoring deep convection are not clear for the Kelvin waves because of their limited influence in the southernmost part of Vietnam (van der Linden et al. 2016b).

Despite major efforts, there still exist considerable knowledge gaps for the rainfall ISO in Vietnam. First, it has been assumed that summer rainfall ISO in the IP regions results from the same mechanism and the spatial contrasts of rainfall ISO are simply induced by topography (Yokoi et al. 2007). However, rain-producing synoptic systems display a number of patterns and are different significantly from the north to south of Vietnam due to the effects of multiple climatic factors. Therefore, the mechanisms of rainfall ISO are expected to be distinct from subregion to subregion in Vietnam, as well as in the IP. Second, heavy rainfall mostly occurs in central Vietnam in early winter but usually occurs in northern and southern Vietnam during summer. While past studies mostly focused on the roles of northerly monsoon in enhancing rainfall ISO that favors the occurrence of heavy rainfall in Vietnam in early winter, no document has addressed the possibilities of extratropical forcing of the rainfall ISO in the country during summer. As a result, further investigations of the characteristics and mechanisms of the rainfall ISO in Vietnam are urgently needed.
In this study, the leading modes derived from EOF analysis of long-term daily rainfall anomaly are used as comprehensive descriptions of the rainfall ISO in Vietnam. Specifically, we focus on 1) the spatiotemporal characteristics of the leading modes and the relations between these modes and heavy rainfall in Vietnam subregions and 2) the differences of extratropical forcing controlling the leading modes. Section 2 describes the datasets and methodology used in the study. The spatiotemporal characteristics of rainfall ISO and their relations with heavy rainfall days are presented in section 3. Next, section 4 discusses the evolution of large-scale patterns associated with the individual leading modes. Finally, conclusions are given in section 5.

2. Data and methodology

a. Data

The high-resolution Vietnam Gridded Precipitation data for the period 1981–2009 were primarily used for a rainfall ISO analysis. These data were constructed at 0.1° × 0.1° latitude–longitude resolution using observations at 481 rainfall stations across Vietnam (Nguyen-Xuan et al. 2016). To focus on the intraseasonal variation, the first three annual harmonics, which best represent most of the seasonal variation of rainfall in Vietnam, were subtracted from the rainfall data. The anomalous rainfall was then smoothed with a 5-day running-mean filter to remove synoptic fluctuations.

Because the gridded rainfall data generally underestimate the intensity of heavy rainfall events, observed data at 73 stations were used to determine heavy rainfall days (Fig. 1). According to the National Center for Hydrometeorological Forecasting of Vietnam, a heavy rainfall day in a subregion is determined if daily rainfall exceeding 50 mm is observed in more than one-half of the total number of observation stations in that subregion. The threshold of 50 mm day$^{-1}$ was chosen to consider the threats of floods and landslides in the country. This criterion was also used by Nguyen-Thi et al. (2012) to determine the heavy rainfall days caused by tropical cyclones in Vietnam. This criterion for the number of observations, that is, over half of the stations, is used to exclude heavy rainfall events induced by local-scale phenomena such as thunderstorms. Variations of the principal components (PCs) are then compared with the variations of heavy rainfall days to identify the correlation between ISO and heavy rainfall in specific Vietnam subregions. For comparability, all variables are also normalized by their standard deviation.

Other major sources of data used in this study were the daily OLR (Liebmann and Smith 1996) obtained through the NOAA satellite and 6-hourly ERA-Interim data (Dee et al. 2011) from ECMWF. The daily average ERA-Interim data were calculated from 0000, 0600, 1200 and 1800 UTC analysis times. The OLR dataset has the spatial resolution of 2.5° × 2.5° latitude–longitude, while the original ERA-Interim has a higher resolution of approximately 0.75° × 0.75° latitude–longitude. For comparison purposes, the ERA-Interim dataset at 2.5° × 2.5° latitude–longitude was used to have the same resolution as the OLR dataset. To extract the intraseasonal time scale signals, a Lanczos bandpass filter (Duchon 1979) was applied to the two datasets. In this study, a 7–25-day period was chosen for the bandpass filter because only that period had peaks that exceeded the 95% confidence level in power spectral density (PSD) analysis applied on the PCs (see more in section 3a).

b. EOF and PSD analysis

It is necessary to classify rainfall ISO patterns to understand ISO activities in different subregions where terrain and climate are complex. EOF analysis is a fruitful tool for this purpose because it helps to regionalize climatic data without losing significant information. Using a correlation or covariance matrix, regions (data points) that have the same atmospheric controls (and, thus, the same variations of climatic variables) are correlated and grouped. The most important features of variables are also obtained by linear combination of variable values in each region. In the present study, an EOF analysis was, therefore, applied to the smoothed anomalous rainfall to classify subregions that encompass distinct characteristics of rainfall ISO. Because the rainfall variance is significantly different among the subregions in Vietnam, the correlation matrix was used in the EOF analysis.

To identify the dominant frequency of rainfall ISO in Vietnam, a PSD analysis was then applied to each PC. The PSD was obtained by computing the autocorrelation function of each PC time series in Fourier space. The Markov red-noise spectrum (Conway and Guy 1996; Cusick and Flahive 1989) and its corresponding 95% confidence level were also calculated. To avoid scale differences, the PCs were normalized by their standard deviation.

c. Criteria for active and break phases

The active and break phases of SISO events are often defined based on time series of filtered rainfall (Fujinami et al. 2014; Hatzusuka et al. 2014; Ramamurthy 1969); however, in order to isolate the rain-producing patterns in Vietnam, the active and break phases in the present study are identified by the 7–25-day Lanczos filtered PCs.
To obtain the high amplitude of the rainfall ISO events, the active (break) phase was determined by a period of at least 3 consecutive days of positive (negative) filtered PCs, and when at least 1 day the absolute filtered PC exceeds 1.0 standard deviation of the filtered PC. There were 212, 305, 332, and 330 active and 200, 311, 319, and 334 break phases detected for PC1, PC2, PC3, and PC4, respectively, over 29 years. On average, there are 6.8, 7.2, 6.6, and 6.9 days in active phases and 8.2, 6.6, 6.6, and 7.2 days in break phases for PC1, PC2, PC3, and PC4, respectively. The days when the filtered PC reached a maximum (minimum) are referred to as day 0 of the active (break) phases. The large-scale patterns associated with ISO events were then computed using the technique of compositing. To focus on statistically significant signals, anomalous fields plotted in figures are tested using the Student’s t test.

3. Leading modes of the rainfall ISO and relations with heavy rainfall

a. Leading modes of the rainfall ISO

According to the scree test (Cattell 1966) and North’s rule of thumb (North et al. 1982), the variance percentage of eigenvalues and sampling errors at 99% confidence level associated with the PCs were estimated (Fig. 2). The significant break of the variance percentage between PC4 and PC5 allows us to establish the first four PCs for retention from the EOF analysis. The first four PCs, which account for 30.3%, 15.4%, 9.1%, and 5.6% of the total variance, respectively, are well separated from each other; therefore, they should be treated as individual subspaces instead of pairs of eigenvectors.

The rainfall ISO regionalization based on EOF analysis exhibits profound influences of topography (Fig. 3). EOF1 has positive values extending along the eastern coast of central Vietnam, with a clear core over the middle part (i.e., Mid-Central; see Fig. 1 for the Mid-Central boundary) where the highest annual heavy rainfall frequency is observed. It is well known that the Truong Son Mountains play a crucial role in enhancing anomalous low-level circulation that causes heavy rainfall in this subregion (Chen et al. 2012b; Nguyen-Le and Matsumoto 2016; Wu et al. 2012). EOF2 has positive values in the North Central and Northern regions and negative values in the South Central subregions, displaying a concentration of rainfall ISO in the low terrain east of the Truong Son Mountains. In a different manner, EOF3 possesses a tripole pattern, with large positive values in mountainous areas of the Northeast and in a narrow band in the South Central and large negative values in the North Central subregion. It is likely that enhanced rainfall exists in the Northeast, which is caused by high mountain ranges in these subregions. Finally, EOF4 shows a pattern with alternative large positive and negative values extending from the north to south of Vietnam, with positive values that mostly cover southern Vietnam. There are two clear local positive maxima in the Central Highlands, where the elevations are relatively higher than the surrounding regions, implying that topography increases the rainfall ISO. Large negative EOF4 values are also observed over the Mid-Central subregion, reflecting the enhancement of rainfall ISO by the Truong Son Mountain (in break phases of PC4).

Because of the orographic effect, in a subregion covered by high EOF values, the rainfall ISO is not always best presented by the corresponding PC. To interpret each PC, the correlations between the PC and the anomalous rainfall in all Vietnam subregions were calculated (Table 1). It has been shown that the first four PCs successively have the highest correlation coefficients with the anomalous rainfall in four separate subregions, that is, Mid-Central, Red River Delta, Northeast, and Southern Plain. Those highest correlation coefficients range from 0.37 to 0.71, which are all statistically significant, suggesting that those PCs are more associated with the rainfall ISO variabilities in the four subregions than in the rest of Vietnam.

To further investigate the characteristics of rainfall ISO, the PSD analysis was applied to the first four PCs to

![Fig. 2. Scree plot of the first 10 eigenvalues from the EOF analysis applied to the anomalous rainfall from 1981 to 2009. The error bars represent the sampling error at the 99% confidence level for each eigenvalue.](image)
identify the dominant frequency of the anomalous rainfall. As a result, the spectrum of these four PCs in separate years displays a considerable year-to-year variation of the rainfall ISO (figures not shown). However, in order to focus on the main characteristic of the rainfall ISO, only the 29-yr mean spectrum was displayed (Fig. 4). Moreover, only spectral peaks between 7 and 25 days exceed the 95% confidence level, indicating the dominance of rainfall submonthly intraseasonal oscillations (SISOs) over all Vietnam subregions. The mean spectral peaks in the 30–60-day range are not statistically significant implying the weak influences of intraseasonal modes greater than 30 days. Thus, the characteristics of the rainfall ISO in Vietnam are principally depicted by submonthly variations instead of two modes, as in other Asian summer monsoon regions. Therefore, the 7–25-day period is chosen for the Lanczos bandpass filter applied to the PCs and our focus the later part of the study is only on large-scale patterns modulating the rainfall SISO.

b. Relations between rainfall SISO and heavy rainfall

The relations between the rainfall SISO and heavy rainfall variation were investigated in some specific subregions where the rainfall anomalies have high correlations with the first four PCs. Figure 6 shows that the filtered PC1 has a clear peak in October when heavy rainfall occurs most frequently in the Mid-Central subregion. The significant increasing trend of the number of normalized heavy rainfall days from September to October and its dramatic drop after October in the Mid-Central subregion is closely in phase with the seasonal variation of the normalized filtered PC1 (Fig. 6a). Therefore, it can be confirmed that the SISO is the dominant factor contributing to the occurrence of heavy rainfall in the Mid-Central subregion.

<table>
<thead>
<tr>
<th>Subregion</th>
<th>PCI</th>
<th>PC2</th>
<th>PC3</th>
<th>PC4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northeast</td>
<td>0.02</td>
<td>0.51</td>
<td>0.45</td>
<td>−0.1</td>
</tr>
<tr>
<td>Northwest</td>
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<td>0.3</td>
<td>0.35</td>
<td>−0.15</td>
</tr>
<tr>
<td>Red River Delta</td>
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<td>0.6</td>
<td>0.14</td>
<td>0.06</td>
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<tr>
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<td>0.37</td>
<td>−0.31</td>
<td>0.09</td>
</tr>
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<td>−0.24</td>
<td>0.17</td>
<td>0.00</td>
</tr>
<tr>
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<td>−0.14</td>
<td>0.09</td>
<td>0.2</td>
</tr>
<tr>
<td>Southern Plain</td>
<td>0.2</td>
<td>−0.29</td>
<td>0.03</td>
<td>0.37</td>
</tr>
<tr>
<td>Mid-Central</td>
<td>0.71</td>
<td>0.00</td>
<td>0.08</td>
<td>−0.14</td>
</tr>
</tbody>
</table>
subregion. Similarly, the normalized filtered PC2 also shows the highest amplitudes in September and displays other peaks in May and July that are strictly coincident with the peaks of the number of normalized heavy rainfall day in the Red River Delta. Furthermore, the trend of the seasonal variation of the normalized filtered PC2 variance is similar to that of the number of normalized heavy rainfall days in the subregions (Fig. 6b). These signals imply the potential of the SISO to trigger heavy rainfall in Red River Delta in summer. The close relationship between the normalized filtered PC4 and the number of normalized heavy rainfall days is also noticed in Central Highlands, where the peaks of the normalized filtered PC4 and the number of normalized heavy rainfall both happen in May, August, and October (Fig. 6e). In the Southern Plain, the enhancement of the number of normalized heavy rainfall days is observed from October to November when the SISO is most active; however, the relationship between the normalized filtered PC4 and the number of normalized heavy rainfall days is not as clear in the Central Highlands (Fig. 6f). In a different manner, correlation between the normalized filtered PC3 and the number of normalized heavy rainfall in the Northeast is only high in the early half of the rainy season (Fig. 6d). It is important to note that while rainfall is enhanced in the Mid-Central subregion in the break phase of the PC2 and PC4, these two modes have weak correlations with heavy rainfall in these subregions (Fig. 6c).

4. Extratropical forcing of the rainfall SISO

a. PC1: Pressure surge from the Siberian high

The evolutions of low-level patterns associated with the PC1 active phases are shown in Fig. 7. On day −8, a
large-scale wave train with alternate positive (A1, A2) and negative anomalous (C1, C2) mean sea level pressures is evident over the Eurasian continent. The wave train develops southeastward to East Asia in conjunction with the northwestward movement of disturbances over the south of the Bien Dong to the IP. Though the scale of the disturbances is small compared to the domain, it still can be identified by the anomalous cyclonic circulation and negative anomalous OLR over the oceanic region. When the anticyclonic anomaly (A2) of the wave train moves across the areas of low air temperature over Mongolia and Lake Baikal, it expands to a great extent and strength that reflects the subseasonal amplification of the Siberian high (Fig. 7c). At the same time, a low anomaly is clearly seen over the Okhotsk Sea. The deepening of the anomalous low–high pressure system yields strong anomalous northerly flows over a broad region of East Asia.

It should be emphasized that from days −4 to 0, the high pressure anomaly from Siberia displays a fast southward movement to eastern China, and then it weakens and moves slowly eastward after reaching 15°N (Fig. 7d). These changes in the propagating-disturbance velocity and direction relate to a “continental shelf wave” dynamic along the slope of the eastern Himalayas (Compo et al. 1999). From days −2 to 0, the eastward movement of the pressure disturbance leads to the shifting of anomalous flows from northerly to northeasterly over eastern China. The anomalous northeasterlies then associate with the preexisting synoptic disturbance and strongly increase horizontal convergence over the Bien Dong. The collaborative effects of pressure surge, tropical disturbance, and topography produce abundant orographic rainfall in central Vietnam on day 0.

It can be seen from Fig. 8 that in the PC1 active phase, the upper-level patterns are characterized by a southward advance of a Rossby wave train originating from the North Atlantic. Because of the enhancement of potential vorticity gradient along the jet stream, it serves
as a waveguide for trapped Rossby waves (Hoskins and Ambrizzi 1993). Compared to the anomalous mean sea level pressure pattern, the wave train exhibits an equivalent-barotropic vertical structure to the west of the Tibetan Plateau and essential baroclinic vertical structure along its eastern slope. As day 0 approaches, the wave train becomes more organized and advances farther southeastward in conjunction with the amplification and southward movement of the low-level high anomaly. According to Takaya and Nakamura (2005) the strengthening of the wave train acts to enhance the surface anomalous northeasterlies and thus brings anomalous cold air to strengthen the preexisting cold air over Siberia. The amplification of the Siberian high, in turn, produces vorticity advection through the troposphere, which reinforces the pressure ridge and cyclonic anomalies downstream and reestablishes the propagation of the upper-level wave train. This process maintains the propagation of the upper-level wave train and sustains the pressure surge over East Asia through interaction with the Siberian high. It should be noted that the strongest pressure surges occur in January–February.

Fig. 6. Seasonal variations of monthly average of heavy rainfall days (gray bars), and 5-day running mean of variance of 7–25-day-filtered PCs (lines; mm$^2$ day$^{-2}$) for the period of 1981–2009. All variables are normalized by their own standard deviation.
(Zhang et al. 1997); however, the TD-type waves that make landfall on central Vietnam are consistent with the withdrawal of the Asian summer monsoon in October–November (Fudeyasu et al. 2006). Therefore, the rainfall SISO in the central region signifies the most active phase in the transition period. In winter, however, continental dry and cold airflow extends southward and dominates the Bien Dong and Vietnam, establishing unfavorable background conditions for convection to develop. Therefore, the boreal winter is the dry season in central Vietnam.

**b. PC2: Pressure surge from northeast China**

Figure 9 presents the temporal evolutions of low-level pattern related to the PC2 active phases. The sequence of composites displays a clear northwestward development of a TD-type wave from the western tropical Pacific to the IP, which is consistent with the life cycle of SISO in the Asian monsoon region (Kikuchi and Wang 2009; Lau and Lau 1990). However, it is interesting to note that during this phase, the TD-type wave is significantly enhanced by movements of large-scale positive and negative pressure anomalies from the polar region toward the equator. More detail can be seen, on day −8, when northern Vietnam is dominated by an anticyclonic anomaly, and a large-scale negative pressure anomaly emerges with a center around 55°N, 130°E and moves southwestward to the northeast of the Tibetan Plateau. On day −6, it elongates on both sides of the plateau.
with a stronger branch on the eastern coast. Meanwhile, active convection accompanied by a cyclonic anomaly is located over the Philippines and moves gradually to northern Vietnam. On the following days, the stronger branch of the pressure disturbance rapidly intrudes into the Bien Dong and merges with the cyclonic part of the TD-wave type, helping intensify the convective activities (Fig. 9c). At the same time, a newly formed positive pressure anomaly with center around $55^\circ N, 130^\circ E$ is noticed and it then follows the same path of the previous negative pressure anomaly several days later. The remarkable change is observed on day 0 when the extratropical positive pressure anomaly reaches the Bien Dong and unites with the anticyclonic part of the TD-wave type, significantly enhancing the convection over northern Vietnam by increasing the pressure gradient between the two pressure anomalies.

The propagation of the large-scale positive and negative pressure anomalies can be considered as southward extensions of continental polar air masses along eastern China in summer. Because of the cold and dry nature of the polar air mass, it is generally associated with clear weather conditions in China. However, when it converges with the maritime tropical air mass that dominates Asian summer monsoon regions, a cyclonic condition is produced. The mechanism for the persistent movement of the cold airflows related to the active phase of PC2 can be traced at a level of 200 hPa (Fig. 10). It is clear that during the phase, there is a southeastward advance of a large-scale wave train from the North Atlantic to the NWP. Though the wave train is a propagating phenomenon, it

![Composite images of 7-25-day-filtered 200-hPa winds (vectors; m s\(^{-1}\)), geopotential (green contours; m\(^2\) s\(^{-2}\)), and unfiltered 200-hPa zonal wind (shaded; m s\(^{-1}\)) corresponding to the active phases of PC1.](image)
greatly resembles the well-known summer wave train bridging Europe and Asia along the North Atlantic and Asian subarctic jet (Ding and Wang 2005). Comparison between lower- and upper-level patterns reveals that the wave is baroclinically unstable. From days $-4$ to $0$, Mongolia is exposed to an anomalous anticyclone that moves from Kazakhstan (Figs. 10c–e). As the wave train becomes more organized, the anomalous northeasterly flows in the northwestern flank of the anomalous anticyclone are further strengthened. The vertical wind shear...
that extends below the flows associated with surface horizontal temperature gradients (figures not shown) triggers the southwestward movement of the polar air mass. This air mass is then driven to southeast China due to the effect of the Tibetan Plateau. Thus, the downstream development of the extratropical wave train associated with topography could lead to the southward intrusion of the polar air mass into southeastern China, which induces positive rainfall SISO in the active phase of PC2.

c. **PC3: Quasigeostrophic lifting of extratropical wave train**

Figure 11 displays the evolution of the filtered low-level patterns corresponding to the active phase of PC3. At the first glance, the dominant feature of the temporal sequence is likely portrayed by the northwestward progress of a TD-type wave from the NWP to northern Vietnam only. Particularly, from days −8 to −6, the convection in northern Vietnam is suppressed, which might be caused by the controlling of an anomalous anticyclone over the subregion. The anomalous anticyclone is then replaced by the anomalous cyclone on day −4 as the TD-type wave moves northeastward (Fig. 11c). At the same time, weak convective activities are noticed to the southeast of the anomalous cyclone and they gradually move northwestward following the anomalous cyclone. A significant change in the pattern is noticed on day −3 (figure not shown), when the anomalous anticyclone over the Bien Dong reaches eastern China, enhancing the anomalous southwesterlies over the northern Bien Dong. Simultaneously, the
anomalous low over northern Vietnam moves westward and then stretches to a narrow band along the foot of the Himalayas, initiating anomalous westerly flows from the Bay of Bengal toward the IP. These changes in low-level circulation are in conjunction with an outburst of convection over northern Vietnam (Figs. 11d,e). The convective anomaly is constantly strengthened and reaches the maximum on day 0. Henceforth, the anomalous anticyclone from the NWP gradually dominates over northern Vietnam and marks the end of the active phase (Fig. 11f).

However, it is important to note that the evolution of the TD-type wave is slower than the rapid outburst of the anomalous convection over northern Vietnam on day −3. We may expect that other factors contribute to the establishment of convection over the key region. To make it more clear, the upper-level patterns of the filtered wind and geopotential height associated with the active phase of PC3 are plotted in Fig. 12. It can be seen that the upper-level patterns are similar to the wave trains along the subtropical jet that connects Europe and Asia in summer (Lu et al. 2002; Enomoto et al. 2003; Fujinami and Yasunari 2004). When the wave moves across the Tibetan Plateau, its vertical structure predominantly associates with baroclinicity (Hu et al. 2016; Park et al. 2015). From days −6 to −4, the southeastward propagation of the wave train leads to a shift in position of the cyclonic anomaly from...
central to southeast China. This cyclonic anomaly creates strong upper divergent flows over southeastern China, as expected for quasigeostrophic (QG) uplift by vertical wind shear. On day \( t = 2 \), as the wave train propagates southeastward, the upper-level divergent flows intruded into southeast of China, consistent with the outburst of the convection in northern Vietnam in Fig. 11d.

To prove that argument, the Q-vector divergence \((-2 \nabla \cdot \mathbf{Q})\) (Hoskins et al. 1978) is applied to diagnose the middle tropospheric vertical motion due to QG forcing. The Q-vector form of the QG omega equation is given below:

\[
\sigma \nabla^2 \omega + f_0 \frac{\partial^2 \omega}{\partial p^2} = -2 \nabla \cdot \mathbf{Q} - \frac{R}{p} \beta \frac{\partial T}{\partial x},
\]

in which \( \omega \) is the pressure velocity, \( \beta \) is the meridional gradient of the Coriolis parameter, \( \sigma \) is measure of static stability, \( R \) is the gas constant, \( T \) is the temperature, \( \psi \) is streamfunction of horizontal wind, and \( \zeta \) is the vertical component of relative vorticity. In the regions of Q-vector convergence, a synoptic-scale ascent is found. From Fig. 13, the areas of positive \(-2 \nabla \cdot \mathbf{Q}\) are noticed over southeast China, which is slightly north of the maximum low-level convergent flows. Because the anomalous

![Fig. 12. As in Fig. 8, but for PC3.](image-url)
Q-vector convergence tilts poleward with height because of the nongeostrophic effect (Yin and Battisti 2004), the QG forcing probably plays an important role in initiating the low-level uplift over southeast China. The shape and propagation of the wave train are better seen at the upper-level pattern of the anomalous circulation in Fig. 15. The similar locations of the cyclonic and anticyclonic anomalies at lower and upper levels demonstrate the barotropic nature of the wave.

The movements of the TD-type wave accompanied by convection are in the same direction as the extratropical wave train from the North Pacific, indicating the covariability of atmospheric circulation between the tropics and midlatitudes that resembles the linkage found by Fujinami et al. (2014). A possible interpretation for this interaction is that the extratropical wave train intensifies the TD-type wave via the increase in meridional pressure gradient. Specially, from day $-4$ to $-2$, a low-level anticyclonic anomaly (a part of the extratropical wave train) moves from the south of Japan to eastern China and strengthens the preexisting cyclonic anomaly (a part of the TD-type wave) over the Bien Dong. The enhanced cyclonic circulation causes stronger low-level convergence, hence, leading to the deepening of convection to the south of the Bien Dong. As a result, a dipole structure of anomalous OLR is established to the north and south of Vietnam, reflecting the contrasting pattern of anomalous rainfall in the two subregions. Another important feature should also be mentioned, namely that, in barotropic waves, isobaric surfaces undulate in unison with the passage of the wave. Therefore, the westward propagation of the upper-level wave also establishes a strong cyclonic anomaly over central China (Figs. 15c,d), which builds up the low-level anomalous northwesterlies along the foot of the Himalayas (Figs. 14c,d). These enhanced northwesterly flows direct the moisture supplied from the Bay of Bengal, contributing to the improvement of convection in southern Vietnam. When the rainfall/convection in southern Vietnam reaches maximum on day 0, the subregion is totally covered by strong anomalous westerlies (Fig. 14e). This is consistent with the fact that anomalous westerlies (easterlies) are generally associated with positive (negative) rainfall anomalous over southern Vietnam (figure not shown).

5. Summary

The present study investigates the spatial distribution and temporal variations of the rainfall ISO in Vietnam during the period 1981–2009 using a high-resolution gridded rainfall data. The large-scale patterns and

![Fig. 13. Composite of Q-vector divergence ($-2 \mathbf{V} \cdot \mathbf{Q}$; shaded; $10^{-19}$ Pa s$^{-2}$) at 500 hPa and the 7–25-day-filtered divergent wind (vectors; m s$^{-1}$) at 850 hPa on days (a) $-2$ and (b) 0 associated with the active phase of the PC3. The regions in which the land elevation is higher than 1.5 km are shaded gray.](image)
mechanisms of ISO were also explored by using OLR and ECMWF reanalysis data. The major results are summarized below.

The rainfall ISO in Vietnam differs greatly from one climatic subregion to another due to the presence of regional-scale topography and extratropical factors. The EOF analysis applied to anomalous rainfall shows advantages compared to conventional methods as it helps sort out the four dominant rainfall ISO patterns, recognizes the corresponding rain-producing synoptic systems, and provides quantitative comparisons of rainfall ISO intensity caused by individual systems. Comparison between the filtered PC variance and seasonal variations of heavy rainfall days reveals that the SISO plays a crucial role in favoring the development of heavy rainfall in Vietnam not only in early winter but also in summer. While most all previous studies used a single case to investigate the mechanism of heavy rainfall in Vietnam, which may not uncover the relevant factors, our analysis using long-term daily data provides a comprehensive description of the processes by which the SISO modulates heavy rainfall.

The extratropical forcing of the wave trains along the North Atlantic–Asian–North Pacific jet streams associated with TD-type waves is the key to understanding the mechanisms of the rainfall SISO in Vietnam. The detailed processes can be classified into four types of different mechanisms, which are illustrated in Fig. 16. First,
in early winter, the southeastward advance of the extratropical wave train amplifies the Siberian high that leads to the outbreak of a pressure surge along eastern slope of the Tibetan Plateau. The intrusion of the pressure surge intensifies the preexisting tropical disturbance over the Bien Dong, creating a strong low-level convergence and blowing unstable air of the disturbance into the Truong Son Mountains. A large amount of rainfall is then produced along the eastern central coast because of the topographic barrier effect (Fig. 16a). Second, in the boreal summer, the strengthening of the extratropical wave train triggers the southward excursion of polar air masses, which then converges with the TD-type wave over the Bien Dong. The cyclonic circulation of the TD-type wave is thereby enhanced, generating positive rainfall SISO in the Red River Delta and some parts of northern Vietnam (Fig. 16b). It is important to emphasize that in these first two cases, the Tibetan Plateau plays an important role in steering the pressure disturbances southward due to the “continental shelf wave” dynamic. In a different manner, in the case of PC3, the extratropical wave train moves across the Tibetan Plateau, becomes more baroclinic, and accelerates low-level upward motions north of the northeastern mountainous regions. The enhanced upward motions associate with the northwestward propagation of the TD-type wave, strongly intensify low-level convergence over the mountainous region in the northeast,
and induce positive rainfall SISO in this subregion (Fig. 16c). At last, the upstream development of the extratropical wave train originating from the North Pacific strengthens the convergent flows of the TD-type wave over the Bien Dong through an increase in the meridional pressure gradient. Thus, the convection associated with the TD-type wave are more intensified, and this wave helps bring positive rainfall SISO over southern Vietnam (Fig. 16d).

The low-level cross-equatorial flow plays an important role that links the variability of the South Asian summer monsoon and synoptic systems over the Southern Hemisphere. The flow is considered as a "duct" that transports both moisture and negative potential vorticity from the Southern Hemisphere into the Northern Hemisphere (Rodwell 1997). However, the degree to which the oscillations in the strength of the synoptic systems over the Southern Hemisphere influence the rainfall in Vietnam is not clear, although rainfall in the country, especially in the Southern Plain and Central Highlands, is strongly modulated by South Asian summer monsoon. Further analysis in this important area is needed to have a comprehensive understanding of intraseasonal oscillation of rainfall in Vietnam.


REFERENCES
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